WATER RESOURCES RESEARCH GRANT PROPOSAL

Title: Internal Phosphorus Loading in Ponds.

Focus Categories: SW, WQL, NU

Keywords: Ponds, Phosphorus, Water Quality, Stratification, Anoxia, Nitrogen, Urban Drainage, Radiotracers, Transport in Sediment and Water.

Duration: 3/99 - 3/00

Federal Funds: $33,178

Non-Federal Funds:

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Congressional District: 2nd

Critical Regional/State Water Problem

Glaciation left deranged drainage patterns and myriad small, shallow basins in much of north temperate America. The resulting ponds and small lakes serve as farm, fish, and fire ponds, stormwater detention and retention, water quality renewal basins, wildlife refuges, ice-skating rinks, and as ornaments in commercial and domestic landscapes. The inevitable results of the appeal and usefulness of ponds have been encroachment upon their drainage basins, excess nutrients, and poor water quality. Ponds can provide primary water quality improvement because dissolved phosphorus ($PO4^{-3}$) combines with oxidized iron (Fe^{+3}) to create insoluble compounds that can be buried in the sediments. But, in bottom sediments Fe^{+3} is chemically reduced to soluble Fe^{+2}, making P mobile once more. In deeper lakes, oxygenated water below the photosynthetic zone recycles P back to the sediments. But in shallow ponds P released by sediments is taken up by photosynthetic algae blooms faster than it can be returned to the sediments. Because residence times for water in ponds are short, a significant fraction of P released by sediments can be discharged downstream, creating poor water quality elsewhere.

Light penetration can occur to pond bottoms which absorb this solar heat and temporarily stratify only centimeters above and below the sediment-water interface. Thermally created density instabilities can release anoxic products (e.g. Fe^{+2} and dissolved P) rapidly from sediment into overlying water. The result is internal P loading and worsened water quality both in the pond and downstream. By the time effects of the P-loading are clearly visible, there is little evidence of the thermal gradients and anoxia that caused the internal P- loading and the evidence of the controlling processes (microstratification and destabilization) no longer exist. As natural and artificial ponds are being used increasingly for water quality renewal in urban and suburban landscapes, incidents of internal P loading are becoming more common and more troublesome. Best Management Practices (BMPs) use ponds because they were thought to mimic the dynamics of lakes in retaining P. However, differences in both the scale and response time of small ponds suggest that BMPs involving ponds be re-examined.

Results and Benefits

Until in-pond P loading is understood, defined in terms of its processes, and dynamically constrained by the time constants of the processes, a useful Best Management Practice (the use of ponds in urban/suburban landscapes) is questionable. Understanding the specific controls and driving forces for intermittent thermal stratification and internal P loading from pond bottoms will lead to better management of ponds for the same reasons that understanding external P-loading from drainage basins led to effective management of lakes in the 1970s.

Upon completion of this pilot project, we will have demonstrated (or scientifically refuted) the role of microstratification and destabilization as a control process for internal P-loading in small ponds. Armed with demonstration data, we will seek additional funding through appropriate avenues and will collaborate with the Connecticut Dept. of Environmental Protection (CTDEP) and Dept. of Transportation (CTDOT) in implementing and evaluating BMPs in other ponds (see attached endorsements from CTDEP and CTDOT). Regardless of the outcome of this pilot project, our analytical techniques and the close-interval sampling equipment installed in Mirror Lake will be available to colleagues in three Colleges (Liberal Arts & Science, Engineering, and Agriculture) within the University of Connecticut for demonstrations, environmental science laboratories and graduate student projects.

Nature, Scope, and Objectives of Research

We hypothesize that several related processes contribute to internal P loading in ponds. This pilot project proposes preliminary analyses to determine the presence and magnitude of those processes. We hypothesize that:

1. Cryptic thermal stratification extends into the sediments of small ponds.
2. The thermal stratification enhances anaerobic decomposition.
3. Continued spring warming destabilizes the sediments resulting in P release 'events' from sediments.

Textbook definitions to the contrary, ponds stratify. Two studies (Rich, 1979; Benoit and Hemond, 1996) on shallow water bodies in southern New England demonstrate that solar energy input to the surface of ponds is distributed between heating the water and heating the sediment. 1/3 of the heat reaching mean depth (2.5m) in the shallow (4m) and humic-stained Dunham Pond, CT, is stored in sediments, and the entire water column is a metalimnion (DQ>1oC/m surface to bottom)(Rich 1979). In the deeper (13m) but clear Bickford Reservoir, MA, eddy diffusion is also controlled by a near-bottom density gradient attributed to heat absorption by the sediments (Benoit and Hemond 1996).

During winter the sediments cool significantly. When ice-out and spring warming occurs, the wind can effectively mix the entire water column. In early spring the sediments remain significantly cooler and tend to stabilize the water column (essentially acting as a cold boundary condition) and create a stable density structure from the deep sediment to the pond surface. With stable density stratification, organic degradation typically produces anaerobic conditions in the sediments of these small, eutrophic ponds. In this sense, the sediments act physically and chemically much like hypolimnetic bottom water. However, as spring progresses, the sediments receive radiant solar energy directly, and warm to temperatures that may exceed that of the water column but do not immediately mix (overturn). Thus much higher temperatures can occur within the sediments; these high temperatures drive the chemical decomposition reactions in the sediment at a much faster rate and to much deeper depths. The decomposition of organic matter results in the release of P.

Bacteria continue to oxidize organic matter by using Alternate (to oxygen) Terminal Electron Acceptors (ATEAs) long after oxygen is exhausted. A typical oxygen source and ATEA sequence is O_2, NO_3^-, MnO_2, $Fe(OH)_3$, SO_4^{-2} and CO_2 . Very quickly following anoxia (loss of oxygen), the ATEA is ferric iron (Fe^{+3}) oxide including $FePO_4$ long known to be the ultimate P sink in lakes. When ferric phosphate is used as an ATEA, ferric iron is chemically reduced to soluble ferrous (Fe^{+2}) iron, and PO_4 is found in the dissolved state and available for transport to the water column. The result is much higher concentrations of P in anoxic pond sediments. Thus, prokaryotic biochemistry (anaerobic respiration) initiates chemical processes (redox reactions) that cause aquatic 'soils' (sediments) to release (insoluble) P, a process almost unknown in oxidized terrestrial soils. So when the sediments finally destabilize (and they must), the amount of remobilized nutrients represents a significant internal loading to the pond. The rapid uptake of liberated P by photosynthetic organisms creates conditions for blooms and degradation of pond water quality. If the residence time of water in the pond is comparable to the uptake time for photosynthesis, the anaerobic remobilization of PO_4 can cause export of P downstream and significant reduction of downstream water quality.

The temperature rise that occurs within the sediments during late spring does not immediately mix (overturn) the sediment porewaters. In the water column of a lake, a density instability must overcome the viscosity or frictional resistance of the water. For the sediment porewaters to overturn, the thermal density instability must overcome not only the higher viscosity and frictional forces of the 'fluidized sediment' but also the stable nonthermal density profile of water to sediment --- sediment being more dense than water. This process of pond porewater destratification is deepened by the non-linear variation of water density with temperature. Water becomes increasingly less dense per degree as water gets warmer. Thus, the density change between 24 & 25oC is more than 31 times the density change between 4 & 5oC (Cole 1994:197) and the critical temperature for porewater instability are approached more rapidly at high temperature. Thus the physics of the cryptostratification system delays overturn, enhances chemical reactivity, remobilizes total P, and produces ideal conditions for P-loading events in shallow ponds.

One reason thermal stratification in ponds is cryptic is the widespread use of dissolved oxygen probes to measure both oxygen and temperature. The bottom of the sediment "decomposition reactor" is generally anaerobic, and an experienced operator will avoid "poisoning" the silver electrode with sulfide by sampling below zero oxygen. That effectively prevents sampling of the layer that controls P-loading in ponds. Other reasons pond stratification and P-loading have not been identified and quantified include the rapid and intermittent nature of release events and lack of scientific attention to small ponds. Given the fundamental importance of ponds as a BMP for low cost surface water quality control, the hypothesized processes define a critical potential problem for BMP use of ponds, and a problem of fundamental science suitable for graduate education.

Decades of success for small ponds as water quality and nutrient retention filters results in the accumulation of decades long external P loading in the sediments. In the latter stages of pond succession, remobilization of P by anaerobic respiration enabled by microstratification, can produce very high fluxes of P to the water column (internal loading of P) enabled by thermal instability. The magnitude of internal P-loading is likely closer in magnitude to decades of external input and is a function of (e.g.) sedimentation rate, sediment mixing depths, and the depth of sediment thermal stratification. The more significant the early success of ponds as a BMP the more likely their eventual failure will be just as significant.